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Design of an Automatic Pendulum Velocity Measuring Device Using Light Sensors

Rima Fitria Adiati*[1], Astridea Salwa Haniyah[2], Agus Kartono[3], and Heriyanto Syafutra[4]
[1,3,4] *Department of Physics, Faculty of Mathematics and Natural Sciences IPB University, Indonesia*
[2] *Bachelor of Science Program, Department of Physics, Faculty of Mathematics and Natural Science IPB University, Indonesia*

Corresponding Authors E-mail: rima_adiati@apps.ipb.ac.id

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Abstract

The instantaneous velocity of an object is the rate of change of its position over an infinitesimally small-time interval, making direct measurement with tools like stopwatches impractical. Using two LDR sensors paired with an Arduino, it is possible to measure such small-time intervals effectively. Understanding the maximum velocity of a mathematical pendulum is critical for distinguishing between harmonic and non-harmonic oscillations. To validate the accuracy of the sensor-Arduino system, several experiments were conducted, including comparisons between Arduino measurements and those obtained from a movie tracker, as well as variations in sensor separation distances, initial oscillation angles, and pendulum rope lengths. Results showed a high level of agreement between Arduino and movie tracker measurements for pendulum crossing times. Additionally, the sensor-Arduino system successfully differentiated the effects of varying each parameter while holding others constant. The system demonstrated an accuracy of 97.86% for velocity measurements at a release angle of 5°, with an average recorded velocity of 23.350 m/s. These findings confirm the sensor-Arduino system's capability to reliably measure the velocity of a mathematical pendulum.

Introduction

Experiments on simple pendulum motion, a type of simple harmonic motion, are limited in their measurement parameters. Typically, only the number of swings and oscillation time are measured. In these experiments, time is often measured manually using a stopwatch. However, stopwatches can lead to inaccuracies in time calculations due to limitations of the tool itself and human error. These inaccuracies can result in measured physical quantities being less precise when compared to theoretical values [1].

To address the issue of time measurement, an innovation in the form of automated laboratory equipment capable of measuring time more accurately and automatically is required. One solution that can be implemented is the use of an LDR (Light Dependent Resistor) sensor connected to an Arduino UNO microcontroller [2],[3]. The LDR sensor can detect the movement of an object influenced by changes in the light shining on its surface. In this research, the role of the Arduino UNO is to automate data acquisition and enhance accuracy, which can be easily obtained in large quantities [4].

This research is a modification of previous studies that used a single LDR sensor and a gear motor as the object whose velocity was measured [5]. This modification involves using two LDR sensors connected to an Arduino UNO to measure the instantaneous velocity of a simple pendulum. By using two LDR sensors, it is expected to improve the accuracy of time and velocity measurements. This system is integrated with a velocity data acquisition system to obtain more accurate and reliable results. Additionally, the use of Arduino UNO allows the measurement process to be more automated and reduces errors caused by human error, thereby improving the quality of the practical work and enhancing students understanding of the physics concepts being studied [6], [7], [8].

The objective of this study is to design and implement an automated device using an LDR sensor that accurately measures the instantaneous velocity of a pendulum, and to understand the impact of varying distances on the measured velocity of a pendulum.

Theory and Calculations

Simple Harmonic Motion (SHM) is a type of periodic or oscillatory motion that occurs due to a restoring force, which always opposes changes in position, keeping the object in a state of equilibrium. SHM involves back-and-forth movement through an equilibrium point in a regular pattern. An example of this motion is observed in a pendulum (Figure. 1), which consists of a massless string attached to a bob [9].

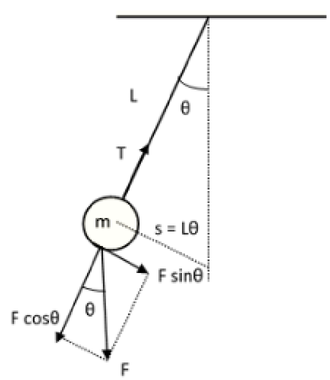

Figure 1. Pendulum oscillation [10]

The period of simple harmonic oscillation depends on the length of the pendulum string and gravitational acceleration, derived from Newton's Second Law, ∑F = m.a, influenced by the pendulum's restoring force, resulting in the simple harmonic motion equation [11]. The angle of displacement also affects the pendulum's period.

$$T = 2\pi\sqrt{\frac{L}{g}} \tag{1}$$

This period equation is only valid for very small displacement angles θ (maximum 10°), assuming $\sin\theta \approx \theta$. $\sin\theta = \frac{s}{L}$. For larger angles, the period is expressed as an infinite series [9].

The potential energy [12], [13] in harmonic motion is derived from its restoring force, which causes the ball to move towards the equilibrium poin [14].

When the pendulum is at its maximum displacement, the value of $v_1 = 0$, because only potential energy is present. From this, the formula for velocity can be derived.

$$v_2 = \sqrt{2gh} \quad (2)$$

$$h = (L - L\cos\theta) \quad (3)$$

Velocity is obtained through the principle of energy conversion using gravitational acceleration, the pendulum's height at a specific angle, and the length of the string [15], [16]. The mechanical energy of simple harmonic motion is:

$$E_m = \frac{1}{2}A^2 m\omega^2\left(\cos^2(\omega t) + \sin^2(\omega t)\right) \quad (4)$$

Based on equation above, the value of $m\omega^2 = k$ and $\left(\cos^2(\omega t) + \sin^2(\omega t)\right) = 1$, so the mechanical energy is:

$$E_m = \frac{1}{2}kA^2 \quad (5)$$

Total energy on simple harmonic motion is directly proportional to the square of pendulum amplitude [5].

Average velocity is the ratio of the displacement that occurs over a certain time interval to that interval. The speed at any given moment is obtained from the average velocity by reducing the time interval to approach 0 [17]. Instantaneous velocity is the velocity at a specific moment with a time interval approaching zero. Its direction is tangent to the curve of the object's trajectory [18].

$$v = \lim_{\Delta t \to 0} \frac{ds}{dt} \quad (6)$$

there
v = velocity (m/s),
t = time (s) , and
s = distance between sensors (m)

Experimental Method

Generally, calculating velocity requires the parameter of distance divided by the time interval. Time is the main parameter detected using LDR sensors in velocity measurement. Previous research used LDR sensors to determine the velocity of a gear motor by dividing the length of the partially covered LDR surface by the time interval (Figure. 2) [5].

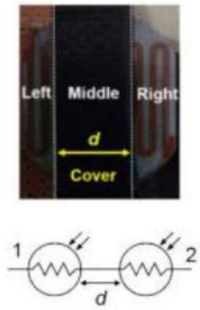

Figure 2. The LDR sensor is partially covered.

Based on this reference, a new concept was developed to obtain the velocity of a moving pendulum automatically and efficiently. This study uses two LDR sensors, a laser light as the light source, and Arduino UNO to support the automation of the practical tool [19]. The velocity value is obtained by dividing the distance between the LDR sensors by the calculated time interval.

The design phase involves gathering the necessary tools and materials and understanding how to program the Arduino UNO board. To create the velocity measurement device for this study, the main components required include a pendulum, two LDR sensors module, two laser diode, power supply module, a 9V battery, an Arduino UNO, and a laptop connected via the Arduino IDE software.

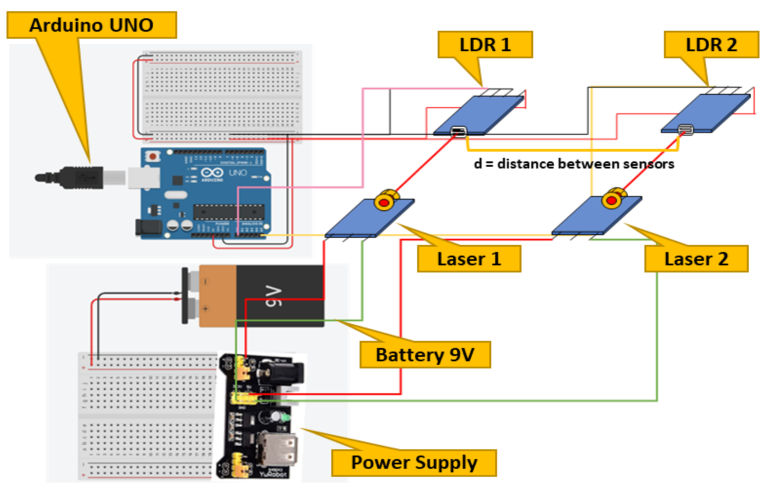

Figure 3. LDR Sensor and Laser Circuit

The next step is setting up the software used, which includes Arduino IDE and Tracker Software [20], [21]. Both software applications are used to collect data when the pendulum starts moving and to detect the velocity values generated by the pendulum. Tracker Software collects data by connecting a camera to the software for more accurate results [22], then compare with the result from Arduino IDE collects data from the Arduino UNO connected to the LDR and laser circuit (Figure. 3).

The combined sensor and laser circuit with a pendulum machine has a string length of 30 cm, 50 cm, 70 cm and a small lead ball with a diameter of 3 cm. The setup of this measuring instrument (Figure. 4) requires variations in the distance between sensors in the form of rails from the slide block bearing and linear rail shaft which can be shifted according to the distance required.

The photoresistor circuit is connected to the Arduino UNO through the Arduino IDE software on a laptop. The photoresistor circuit will be arranged in conjunction with the laser circuit, linking the sensor movement to the Arduino UNO, data collection, and data analysis from several testing stages. Instantaneous velocity measurement is performed by moving the pendulum through two sensors acting as a timer, where the first sensor starts the timing and the second sensor stops it. The travel time obtained will be converted into velocity by dividing the distance between the two sensors by the travel time according to the instantaneous velocity formula.

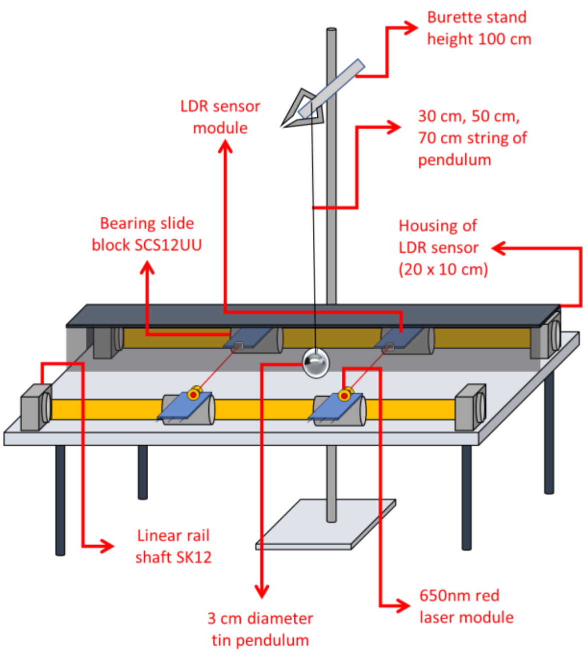

Figure 4. Design of set up experiment automatic pendulum velocity measuring device

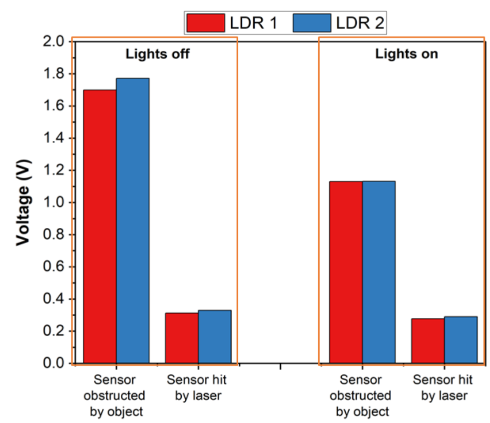

Figure 5. Calibration of LDR Sensors Using Laser Beam

After setting the tool, the equipment needs to be tested to ensure it is ready for use. The testing of the tool is carried out in several stages, starting with the testing of the sensor. The LDR sensor is tested to determine the voltage limits on the LDR when illuminated by a laser, whether the sensor is blocked by a pendulum or only exposed to the laser beam in a room with the lights off and on, to observe the effect of ambient light conditions on the voltage changes detected by sensors 1 and 2. The LDR sensor testing uses an Arduino UNO with the voltage values displayed in the Arduino IDE software. The second testing stage is measuring the time required by the ball to pass through two sensors. This test is conducted to validate the time measurement data, which will be compared with time measurements using the Tracker software to see the consistency between the two software measurements. The detected time will appear in Excel, which is connected to the Arduino IDE. The next stage involves time testing with variations in the distance between sensors (1, 3, 5, 7, 9 cm), string length (30, 50, 70 cm), and angle variations for harmonic and non-harmonic motion.

Results and Discussion

The calibration of LDR sensor is performed by connecting LDR sensor 1 and LDR sensor 2 to the Arduino IDE software under both lights-off and lights-on room conditions. The response of the two LDR sensors shows a voltage change under two room lighting conditions (Figure. 5). In the lights-off condition, when the sensor is obstructed by an object, both sensors show a high voltage, reaching up to 1.5 V. When the sensor is exposed to laser light, the voltage drops to below 0.5 V due to the significant intensity of the red laser. In the lights-on condition, the sensor obstructed by the object produces a lower voltage than in the lights-off condition, less than 1.5 V. The LDR sensor exposed to the laser light in the lights-on condition shows the same voltage drop as in the lights-off condition.

Based on the Figure. 5, the room conditions with the lights off and on do not significantly change the voltage when the laser light hits the sensor. However, a significant voltage change occurs when the laser does not hit the sensor, as no other light hits the sensor besides the ambient room light. Thus, the room light intensity only slightly affects the sensor voltage compared to the laser diode light because the laser diodes light intensity is much greater than the room light intensity. The difference in voltage change under various light intensity conditions aligns with the theory of the used LDR sensor circuit, which is a voltage divider circuit. This circuit produces a voltage relationship inversely proportional to the room light intensity. Time interval measurement is based on the change of voltage over time, with the details are shown in Figure. 6.

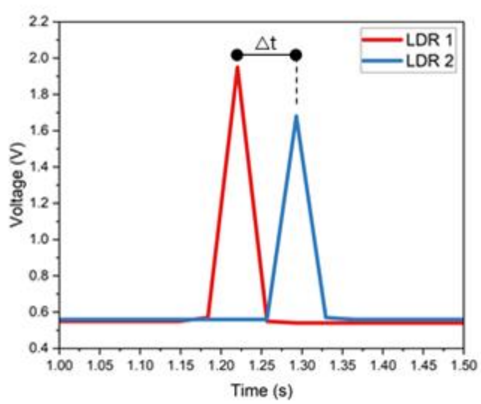

Figure 6. Time interval measurement on Arduino and it is observed that there is a voltage change over time as the object begins to close sensor 1 and moves towards sensor 2. This graph is used to calculate the value of Δt by measuring the time difference at the peak voltage between sensor 2 and sensor 1 using Arduino.

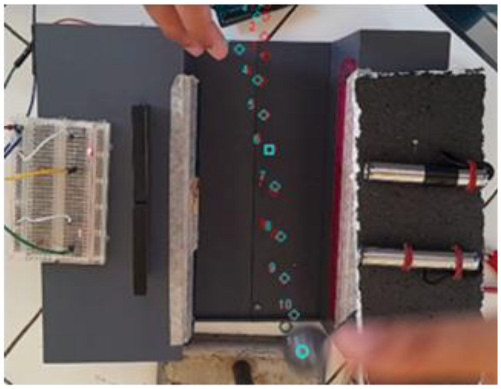

Figure 7. The analysis process on Tracker involves determining the time when the pendulum passes through both sensors to obtain the value of Δt, specifically by identifying two points where the pendulum crosses the sensors and calculating the time difference between these two points. The Δt values from both measuring instruments are very close with an accuracy of 98.13%.

The time measurement in the next variation will establish the relationship between the distance between sensors and Δt to obtain the velocity of the moving pendulum. The time validation data at this stage uses the same release angle, pendulum diameter, and string length as the time validation test on the Tracker (Figure.7).

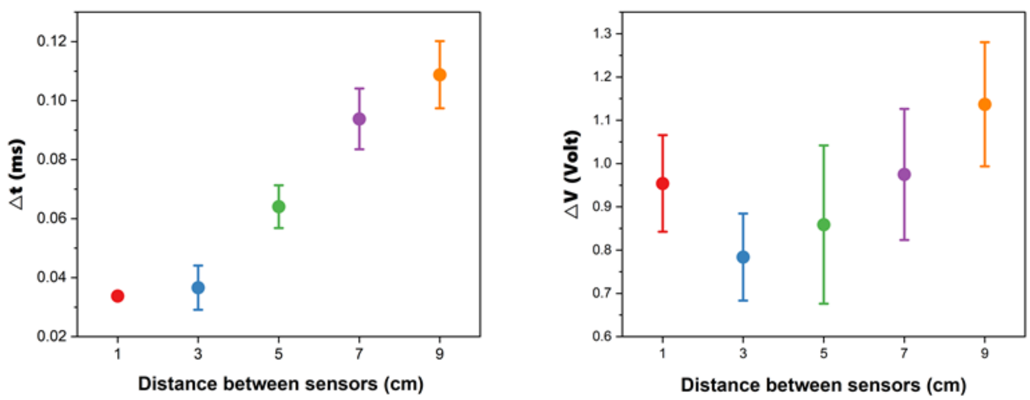

Figure 8. Graph of time and voltage change versus distance between sensors

Based on Figure. 8, the time increases as the distance between the sensors increases. The graph of the ΔV relationship shows a linear increase from 3 to 9 cm. The farther the distance, the greater the voltage change. However, there is a difference at the 1 cm distance, where the voltage change is greater than at other distances.

After analyzing the time interval and voltage change, the next step is to analyze the moving pendulum's velocity to understand the relationship between velocity and sensor distance (Figure. 9). The graph shows that velocity decreases in the range of 3 to 7 cm. Velocity here is calculated using the formula $v = \frac{d}{\Delta t}$, where d is the distance between the sensors, and Δt is the time taken for the pendulum to pass between the two sensors. However, at 9 cm, the pendulum velocity increases again. This may be due to the excessively large distance between sensors, causing the sensor response to be inaccurate. A difference in velocity data is also observed at the 1 cm distance, as seen in the previous graph.

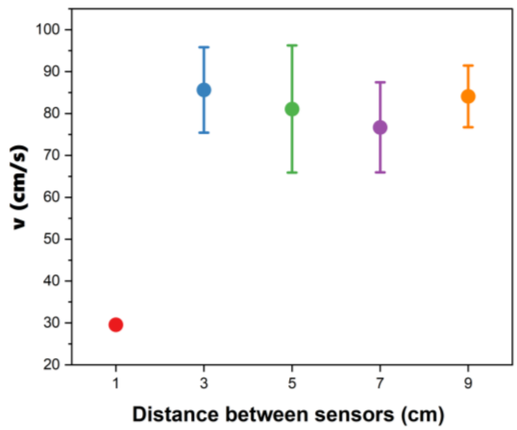

Figure 9. Graph of velocity versus distance between sensors

Based on the three graphs, at distances of 1 cm and 3 cm, there is a similarity in the Δt data, a decrease in voltage change (ΔV), and an increase in velocity (v). This is likely due to the pendulum's length being 3 cm. Thus, at a distance of 1 cm, the data received by the two sensors may not be precise because the distance is smaller than the length of the pendulum passing through the sensors. Therefore, the optimal distances that can be accurately measured by both sensors are 3 cm, 5 cm, and 7 cm.

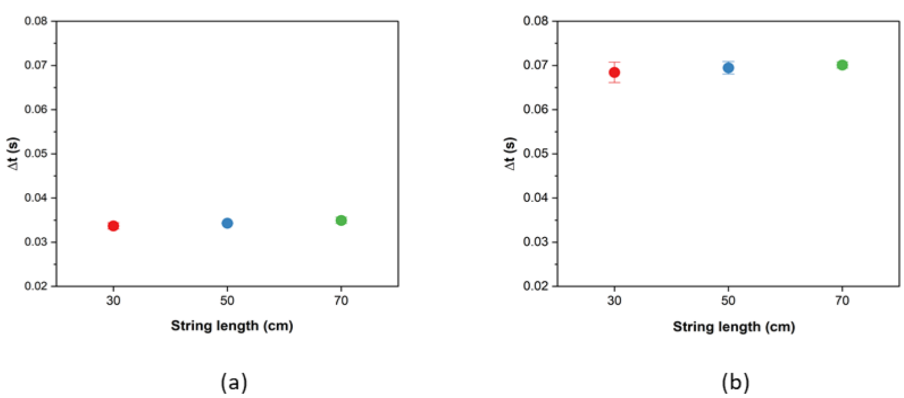

Figure 10. The graph of Δt against the length of the string at a distance between sensor are (a) 3 cm and (b) 5 cm

Time measurement on string length must to be tested to determine the effect of the length of the string on the velocity of the pendulum. The testing was conducted with a constant release angle of 30°, and the pendulum length was varied to 30 cm, 50 cm, and 70 cm [23]. The test results show a direct relationship between the length of the string and the Δt value (Figure. 10). This means that the time required for the pendulum to move from one point to another increases as the string length increases. This is consistent with previous observations regarding the effect of distance on the Δt value, where the greater the distance between the sensors and the length of the string, the Δt value also increases proportionally.

The distance between the sensors is 5 cm, with variations in the string length of 30, 50, and 70 cm, yielding times of 0.0684 ± 0.0019 seconds, 0.0695 ± 0.0011 seconds, and 0.0701 ± 0.0006 seconds, respectively. This means that the optimal string length at a sensor distance of 5 cm is 70 cm. However, there is a difference at a sensor distance of 3 cm, where the most optimal string length is 50 cm, with a time value of 0.0343 ± 0 seconds, meaning that in 5 repetitions, the time value remained the same. Meanwhile, the string length of 30 cm resulted in a time of 0.0337 ± 0.0006 seconds, and the string length of 50 cm resulted in a time of 0.0349 ± 0.0006 seconds, as shown in Figure. 11.

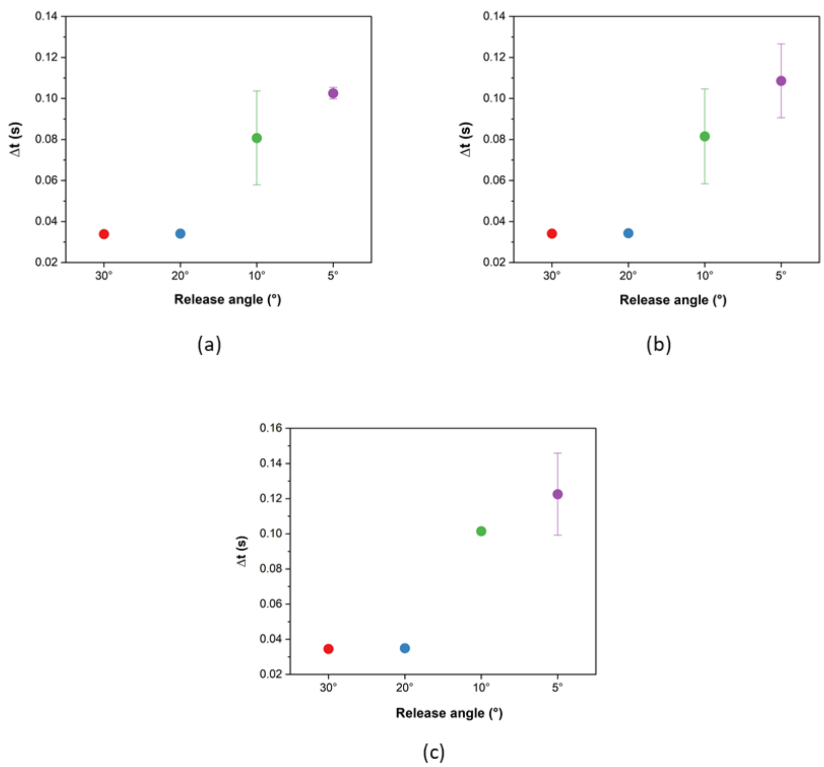

Figure 11. Graphs of Δt against pendulum length and variation in angle: (a) 30 cm, (b) 50 cm, (c) 70 cm. The figure shows an inverse relationship between the release angle and Δt, and a direct relationship between pendulum length and Δt. Harmonic motion release angles, such as 5° and 10°, exhibit higher Δt compared to angles > 10°. Thus, it is known that the pendulum requires more time at harmonic motion angles. Therefore, angle variation, sensor distance, and pendulum length significantly effect of Δt and the velocity of the pendulum's motion.

Pendulum Velocity

The pendulum velocity was measured with a 3 cm distance between sensors and a pendulum length of 70 cm. Table 1 shows the instantaneous velocities at 5° angle as 25.21 cm/s, while the theoretical velocity is 23.44 cm/s. In contrast, at 30° angle, which results in higher swing amplitude and velocity, it measures 53.57 cm/s compared to the theoretical velocity of 136.65 cm/s. These data indicate that instantaneous velocity can be automatically measured using LDR sensors for both harmonic and non-harmonic motions. However, the velocity values need to be compared with the theoretical pendulum velocity formula to assess the accuracy of the measurement tool.

The calculation of velocity automatically shows an accuracy of approximately 90% for simple harmonic motion, whereas non-harmonic motion achieves only 40% accuracy. The measurement of instantaneous velocity in this study is considered linear motion with a nearly straight swing path because the angle is less than 10° and the swing height at certain angles is less than 1 cm. The accuracy of velocity at 30° angle is lower due to inaccuracies in the measured time interval and the influence of swings that are too far from the LDR sensor. The more curved swing of the pendulum results in a swing height greater than 1 cm, which cannot be considered as linear motion.

Table 1. The instantaneous velocity of a pendulum at angle variations of 5° and 30°

No	Angle Variation (°)	Instantaneous Velocity (cm/s)	Average	Accuracy
1		25.210		
2	5	23.256	23.350	97.86%
3		21.583		
4		53.571		
5	30	53.571	56.548	41.70%
6		62.500		

The analysis of pendulum velocity data at 5° and 30° swing angles shows significant differences in motion patterns and velocity values. At 5° swing angle, the pendulum velocity tends to be larger and varies between 2.74 cm/s to 25.21 cm/s, indicating harmonic motion characteristics with greater velocity changes around the equilibrium point. Meanwhile, at 30° swing angle, the pendulum velocity ranges from 3.02 cm/s to 53.57 cm/s, with the highest values achieved near the equilibrium point.

The time measurement of an object using one LDR sensor is almost the same as the time measurement of a pendulum with two LDR sensors, which is around 30-40 ms [5]. However, when measuring speed with a single LDR sensor, the size of the object passing through the sensor significantly affects the speed measurement. This could be due to the small portion of the sensor that is covered compared to the distance between the sensors when using two LDR sensors.

Similar setups have been demonstrated using Arduino microcontroller and sensors. Sanjaya et.al. [24] demonstrated measuring gravitational acceleration using ultrasound sensor. The apparatus accurately measures g equals to 9.811±1.067 m/s^2. Yulkifli et.al. [25] also measure gravity acceleration using photogate sensor, with the accuracy and precision of the experiment system are 98.76% and 99.81%, respectively. Using HC-SR04 ultrasonic sensor to measure the length of the string and an FC-51 infrared sensor to measure the period, Fauzi et.al. [26] obtained a precision of 94.9%. and accuracy of 99%. Period measurement with accuracy ranging from 93% to 97% also demonstrated by Sudarmanto et.al. [27] using NodeMCU and Blynk application.

Overall, the data shows that smaller swing angles result in more harmonic motion with more consistent velocity fluctuations, whereas larger swing angles exhibit more extreme velocity variations due to the pendulum's path. Apart from the pendulum's path, factors influencing instantaneous velocity include programming algorithms in Arduino IDE that may not be precise enough, ambient lighting, and motion caused by Earth's rotation.

Conclusion

This automatic pendulum velocity measuring device, utilizing an LDR sensor, effectively detects pendulum movement by sensing changes in reflected light intensity. Optimal sensor placement at 3 cm distance and small angles (<10°) yield the most accurate velocity measurements (97.86% accuracy) compared to larger angles (41.70% accuracy). This device can automatically measure the instantaneous velocity of a released pendulum. However, oscillatory or non-harmonic motions may reduce accuracy. Factors like programming algorithms, ambient light, and environmental vibrations can also influence results. Future research should focus on refining algorithms and sensor selection for practical applications.

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